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Early-warning signals for catastrophic soil degradation

Derek Karssenberg
Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, Netherlands
(d.karssenberg@geo.uu.nl)

Many earth systems have critical thresholds at which the system shifts abruptly from one state to another. Such critical transitions have been described, among others, for climate, vegetation, animal populations, and geomorphology. Predicting the timing of critical transitions before they are reached is of importance because of the large impact on nature and society associated with the transition. However, it is notably difficult to predict the timing of a transition. This is because the state variables of the system show little change before the threshold is reached. As a result, the precision of field observations is often too low to provide predictions of the timing of a transition. A possible solution is the use of spatio-temporal patterns in state variables as leading indicators of a transition. It is becoming clear that the critically slowing down of a system causes spatio-temporal autocorrelation and variance to increase before the transition. Thus, spatio-temporal patterns are important candidates for early-warning signals.

In this research we will show that these early-warning signals also exist in geomorphological systems. We consider a modelled vegetation-soil system under a gradually increasing grazing pressure causing an abrupt shift towards extensive soil degradation. It is shown that changes in spatio-temporal patterns occur well ahead of this catastrophic transition.

A distributed model describing the coupled processes of vegetation growth and geomorphological denudation is adapted. The model uses well-studied simple process representations for vegetation and geomorphology. A logistic growth model calculates vegetation cover as a function of grazing pressure and vegetation growth rate. Evolution of the soil thickness is modelled by soil creep and wash processes, as a function of net rain reaching the surface. The vegetation and soil system are coupled by 1) decreasing vegetation growth with decreasing soil thickness and 2) increasing soil wash with decreasing vegetation cover. The model describes a critical, catastrophic transition of an underexploited system with low grazing pressure towards an overexploited system. The underexploited state has high vegetation cover and well developed soils, while the overexploited state has low vegetation cover and largely degraded soils.

We first show why spatio-temporal patterns in vegetation cover, morphology, erosion rate, and sediment load should be expected to change well before the critical transition towards the overexploited state. Subsequently, spatio-temporal patterns are quantified by calculating statistics, in particular first order statistics and autocorrelation in space and time. It is shown that these statistics gradually change before the transition is reached. This indicates that the statistics may serve as early-warning signals in real-world applications. We also discuss the potential use of remote sensing to predict the critical transition in real-world landscapes.